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STRENGTHENING OF PHOSPHATE CERAMIC FOAM BY SILICON CARBIDE WHISKERS

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Translation of "Uprochneniye fosfatnoy penokeramiki nitevidnymi kristallami karbida kremniya," IN: Mekhanika Polimerov, No. 2, 1978, pp. 253-256. 78A42871

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16. Abstract

The paper assesses the influence of additions of SIC whiskers on the elastic modulus and flexural strength of phosphate ceramic foam. It is shown that the incorporation into the material composition of even small amounts (2.4 vol%) of SIC whiskers enhances the impact toughness and heat resistance of the ceramic foam. A123 vol% SIC whiskers leads to more than threefold increase of the flexural strength. Strengthening of the phosphate ceramic foam is due to the fact that the whiskers hinder the propagation of matrix crack by increasing the work of matrix fracture. The whiskers reinforce only that volume of material which is considered by solid matter, whereas they do not reinforce the pores.

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STRENGTHENING OF PHOSPHATE CERAMIC FOAM BY SILICON CARBIDE FIBERS /253

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Ceramic foams based on phosphate binders (PB) have low thermoconductivity and high melting temperature, and thus can be used for thermoprotection. However, in view of the low heat resistance, impact viscosity, and strength of these materials, their use is limited. Theoretical and experimental research [1-3] showed that reinforcement of the ceramic matrix with small amounts of high-tenacity fibers can substantially enhance the resistance of the ceramic foam to impact heat and mechanical stress. It was also shown [4] that fibers increase the flexural strength of the material. The fibers reinforce the ceramic foam by hindering the propagation of the matrix crack and increasing the work of the matrix fracture.

In connection with this, we attempted to improve the properties of ceramic foam by reinforcing it with high-tenacity and high-elasticity silicon carbide fiber crystals (FC) with the mean diameter of 0.35 μm and mean length of 0.1 mm (elasticity module 40,000 kg/mm^2, tensile strength 1000 kg/mm^2). We discovered that the addition of small quantities (2.4 volume %) of SiC fibers to ceramic foam enhances its impact viscosity and thermoresistance.

The present article examines the effect of SiC addition on the flexural strength of phosphate ceramic foam. It also asses-

ses the possibility of applying the reinforcement mechanism discussed in #4 to ceramic foam.

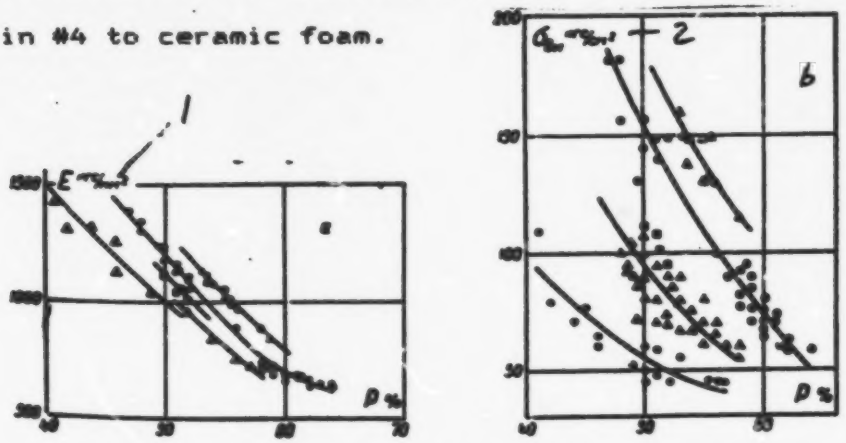

Fig. 1. The relationship between the elasticity modulus (a) and flexural strength (b) of composite ceramic foam and porosity. a: △ - PB; ▲ - PB + 2.4% FC; □ - PB + 4.7% FC; ● - PB + 9.1% FC; ○ -PB + 12.3% FC; b: ● - 0% FC; ▲ - 2.4% FC; □ - 4.7% FC; ○ - 9.1% FC; △ - 12.3% FC.

1 - kg/mm^2; 2 - kg/cm^2

According to #4, the strength σ_c of a fragile composition /254 reinforced with high-tenacity fibers is determined by the following formula:

$$\sigma_c = \sigma_m \frac{E_c}{E_m}, \qquad (1)$$

where σ_c, Em - strength and elasticity modulus of the matrix, respectively; E_c - elasticity modulus of the composition. $\sigma_m = \sigma_{m_0}\sqrt{1+\gamma_f/\gamma_0}$ shows the relationship between the strength of the reinforced and non-reinforced matrices, where γ_0 - the work of the non-reinforced matrix fracture; γ_f - fibers' input into the work of the matrix fracture.

Since the elasticity modulus and strength of ceramic materials depend significantly on their porosity, the change in these properties due to the addition of SiC fibers should be examined taking into account permanent porosity of the material. In this connection, we initially built graphs

showing the relationship between the properties of the ceramic foam based on phosphate binders and its porosity (fig.1), and then used these graphs to determine the relationship between the elasticity and strength of the material and the FC volume percentage (fig.2).

Experiment findings show that the elasticity modulus and flexural strength of the composite ceramic foam decrease as porosity increases and increase as the amount of reinforced fibers increases. The addition of 12.3% of SiC fibers to the ceramic foam results in a threefold increase in the flexural strength of the material.

According to #4, there is a linear correlation between the elasticity modulus of the composition reinforced with fibers of finite length and the amount of fibers in the material:

$$E_c = E_m\left[1+V_f\left(\frac{E_f}{E_m}n_\theta n_l - 1\right)\right]. \qquad (2)$$

Here, E_f, V_f - elasticity modulus and fiber volume percentage; n_θ - coefficient of fiber orientation; n_l - coefficient of fiber use during maximum matrix stress;

$$n_l = \frac{l}{2l_1} \quad \text{when} \quad l<l_1; \qquad n_l = 1-\frac{l_1}{2l} \quad \text{when} \quad l>l_1,$$

where l - fiber length; l_1 - critical length determined from $l_1 = d\frac{\sigma_m E_f}{2\tau E_m}$ (d - fiber diameter; τ - shear strength of the fiber-matrix bond). The difficulty of research precludes the experimental analysis of τ, and thus its value was estimated. According to #5, in most ceramic systems τ does not depend on the fiber material and is equal to $\tau \approx 1/4\sigma_{m\,flex}$. In our study, with porosity p=0.5, τ was assumed to be 15 kg/cm^2. If E_f = 40,000 kg/mm^2, Em = 1,000 kg/mm^2, and d = 0.35 μm, then l_1 is 28 μm. In our case, $l \gg l_1$ and $n_l \approx 1$.

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For three-dimensional chaotic fiber distribution $n_\theta \approx 1/3$. Then, equation (2) can be rewritten as: $$E_c = E_m\left[1 + V_f\left(\frac{1}{3}\frac{E_f}{E_m} - 1\right)\right].$$

Substituting numerical values for Ef, Em, we obtain:

$$E_c = 1000(1 + 12{,}3V_f) \quad \text{kg/mm}^2 \tag{3}$$

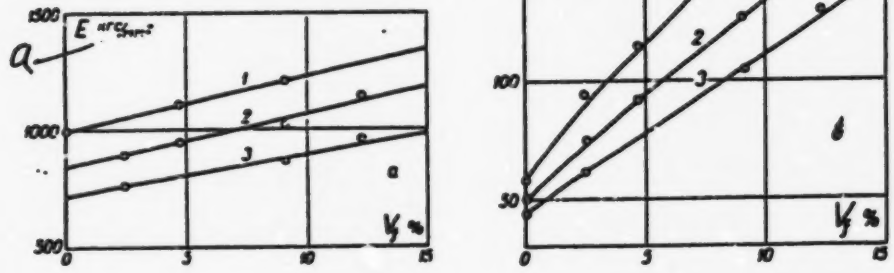

Fig.2. The relationship between the elasticity modulus (a) and flexural strength (b) of composite ceramic foam and the volume percentage of SiC fibers. P = 50% (1); 53% (2); 56% (3).

a - kg/mm^2

However, the value of the increase in the elasticity modulus accompanied by the increase in V_f (see fig.2-a) is lower in the experiment than as determined by equation (3). We can explain this phenomenon if we take into account that SiC fibers reinforce only the volume of the ceramic foam matrix and not the pores; this is also confirmed by the fractographic analysis (fig.3). Then we can say that:

$$E_c^0 = E_m^0\left[1 + V_f\left(\frac{1}{3}\frac{E_f}{E_m^0} - 1\right)\right],$$

where E_c°, E_m° - elasticity moduli of the composition and matrix at zero porosity.

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According to #6, the relationship between the elasticity modulus of the ceramic material and its porosity can be described by the following equation:

$$E = E^0 e^{-ap},$$

where parameter $a \approx 3$. Then, $E_m = E_m^0 e^{-ap}$; $E_c = E_c^0 e^{-ap}$ and, consequently:

$$E_c = E_m \left[1 + V_f \left(\frac{1}{3} \frac{E_f}{E_m} e^{-ap} - 1 \right) \right]. \qquad (4)$$

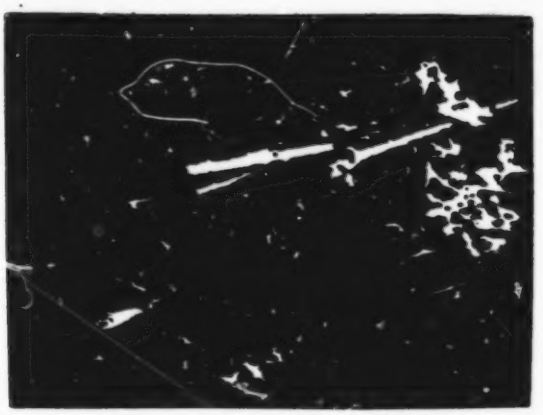

Fig.3. The fracture surface of phosphate ceramic foam reinforced with 9.1% SiC fibers.

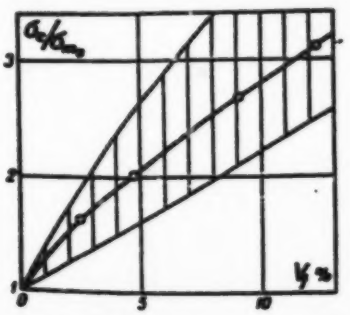

Fig.4. The comparison between the experimental values of flexural strength of composite ceramic foam and the values from formula (6) at porosity p = 0.5. Circles - experimental values; shaded region - formula (6) values with l_f =5-10 μm, γ_0 =10-40 J/m .

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By substituting numerical values into equation (4), we obtain for p= 0.5: $E_c = 1000(1+1{,}97V_f)$ kg/mm^2. This formula is quite satisfactory in describing the experimental findings.

Fractographic analysis (see fig.3) shows that during the /256 fracturing of the composite ceramic foam, SiC fibers are pulled out of the matrix. In this case, according to #4:

$$\gamma_f = \frac{1}{6}\sigma_f V_f \frac{l}{l_2} l_\tau \text{ when } l < l_2; \qquad \gamma_f = \frac{1}{6}\sigma_f V_f \frac{l_2}{l} l_\tau \text{ when } l > l_2,$$

where σ_f - strength of the reinforcing fibers; l_τ - the degree of crack opening; l_2 - critical length determined from the equation $l_2 = d\frac{\sigma_f}{2\tau}$. Assuming that d = 0.35 μm, σ_f =100,000 kg/cm^2, τ =15 kg/cm^2, we find that l_2 = 1.17 mm. In our case $l < l_2$ and

$$\gamma_f = \frac{1}{3}\tau V_f \frac{l}{d} l_\tau. \qquad (5)$$

By substituting equations (4) and (5) into equation (1), we obtain:

$$\sigma_c = \sigma_m \sqrt{1 + \frac{\tau V_f l l_\tau}{3 d \gamma_0}} \left[1 + V_f \left(\frac{1}{3}\frac{E_f}{E_m} e^{-\alpha\gamma} - 1\right)\right]. \qquad (6)$$

Values l_τ and γ_0 in equation (6) were not determined experimentally. In most ceramic materials, l_τ = 5-10 um, γ_0 = 10-40 J/m^2. By substituting these ranges of l_τ and γ_0 values into equation (6) we obtained the range of theoretical values of the strength of composite ceramic foam. Fig.4 shows that the experimental values of strength lie within the region determined using equation (6) and, consequently, can be explained by the action of the reinforcement mechanism suggested in #4. The closest concurrence of the experimental and theoretical findings occurs when we use l_τ=7 μm and γ_0=20 J/m^2.

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